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Vented Tank Resupply Experiment: Flight Test Results

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This paper reports the results of the vented tank resupply experiment which was flown 19 May 1996 as a payload on the space shuttle mission STS 77. The vented tank resupply experiment examines the ability of vane propellant management devices to separate liquid and gas in low gravity. The vented tank resupply experiment used two clear 22.7 liter (0.8 ft^3) tanks, one spherical and one with a short barrel section. Refrigerant 113 was transferred between the two tanks. The tanks were also periodically vented to space. Tests included the retention of liquid during transfer, liquid-free venting, and recovery of liquid into the propellant management devices after thruster firing. Liquid was retained successfully at the highest flow rate tested (10.33 l/min). Liquid-free vents were achieved for both tanks, although at a higher flow rate (4.51 l/min) for the spherical tank than for the other (1.13 l/min). Recovery from a thruster firing which moved the liquid to the opposite end of the tank from the propellant management devices was achieved in 30 s.

I. Introduction

THE process of resupply involves transferring liquid into either empty or partially full tanks. The resupply of tanks in low gravity poses several technical challenges. Chief among these are the uncertainty of liquid and vapor distributions in a tank in low gravity and the need to keep the operating pressure of the tank low to reduce tank mass. When filling a tank in a normal gravity environment, a top vent is kept open to vent the vapor generated during the fill process, thereby maintaining a low tank pressure. In a low-gravity environment, venting only gas is difficult because the force of gravity no longer separates the gas and liquid. In addition to venting vapor large amounts of liquid may be dumped overboard. Unbalanced torques produced by venting two-phase flow may cause the spacecraft to tumble out of control (this occurred on Atlas Centaur 4 [1]). One way to avoid these problems is to use a vane propellant management device (PMD) to separate liquid and gas [2]. This PMD uses the capillary forces between the liquid and the vane device to control the liquid position inside the tank. If the PMD is designed such that the liquid is retained over the inlet, and the gas is oriented around a vent tube, a tank may be directly vented to space even during resupply. The vented tank resupply experiment (VTRE) was designed to study such a design and determine its capabilities and limitations. The VTRE was launched on STS-77 on 19 May 1996 as part of a cross bay hitchhiker (HH) bridge payload called the Technology Experiments for Advancing Missions in Space (TEAMS). Resupply issues studied by VTRE included the following. The first issue was retention of liquid during transfer over a possible range of 2.27–10.33 l/min in both spherical tanks and those with a cylindrical barrel section. Liquid retention was also tested with the tanks empty and partially full (20%) at the start of the test. The next issue was liquid-free venting of 90 and 20% full tanks over a gas flow range between 0.286 and 7.14 l/min in the presence of dissolved gas and boiling in the liquid. The final issue was the recovery of liquid into the PMD after thruster firing in excess of the PMD retention capability (estimated at 10^{-4} g acceleration).

II. Background

Vane-type PMD's have been used to provide gas free liquid for spacecraft since 1962 [3]. Examples include the Viking Orbiter [4], communications satellites [5,6], Mars Global Surveyor [7], and the Cassini space probe [8,9]. The ability of the vane device to drain only liquid has been extensively investigated in the past. The Viking Orbiter PMD [4] was also designed to provide a means of direct tank venting. This capability was verified in drop tower tests, but not used in-flight. After the Viking a series of studies were begun to better understand and optimize PMD designs. A priority of these tests was designs to vent a tank during resupply. Multiple series of tank PMD's were designed and tested in a drop tower to determine their effectiveness [10]. The best option was found to be a close variant of the Viking Orbiter PMD (a series of thin vanes around a central standpipe). To further advance the technology a series of flight tests were conducted onboard the NASA Johnson Space Flight Center (JSC) KC-135 test bed [11]. Here a much larger scale system (31.8 cm diam vs 7.62 cm in the drop tower tests) was tested for 5–10 s of low-g (gravity). The inflow patterns appeared to scale geometrically between the two sizes, but the duration of the venting tests was too short to provide meaningful data.

The second flight of the fluid acquisition and resupply experiment (FARE II) [12] also investigated vane PMDs. FARE II flew onboard STS 57 as a mid-deck experiment. FARE II showed that very high final fill levels (greater than 97% at an inflow rate of 0.95 l/min) could be achieved in the tank when filling with water and with the vent open (the maximum stable inflow rate was found to be ~1.5 l/ min). Because the vapor pressure of room temperature water is low and the water used in FARE did not contain large amounts of dissolved gas, the ability of the FARE vanes to move bubbles to the free surface during venting was not challenged.

The VTRE was developed as a part of the NASA In-Space Technology Experiments Project (IN-STEP) to investigate PMD technology further. VTRE was a joint effort between the NASA Lewis Research Center (renamed NASA Glenn Research Center abbreviated GRC) and Lockheed Martin Space Systems (LMSS). The objectives of VTRE were to study the resupply process from

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empty to full, to see how volatile liquids and the presence of dissolved gasses affect the venting process, and to see how quickly PMD devices recover liquid after it is forced out of the PMD by thruster firings.

III. Experiment Description

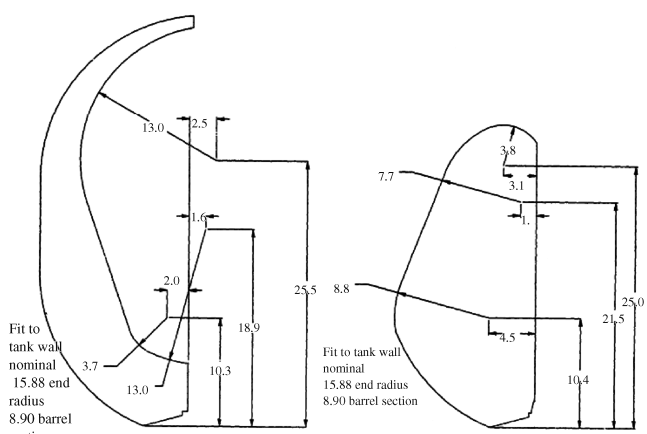
The experiment hardware primarily consisted of two 22.7 liter (0.8 ft^3) clear acrylic tanks with vane-type propellant management devices. The test liquid was a red dyed Refrigerant-113 which provided the best simulant for both storable propellants and for cryogenic liquids. It has a much higher vapor pressure at room temperature than water and will wet the tank walls like the liquids of interest. The red dye enhanced the ability to record video of the fluid motion during both the inflow and the outflow of the liquid from the tanks. Two test tanks of equal volume were used. One tank was a 35.6 cm (14 in.) inner diameter sphere (test tank B) whereas the other was a 31.8 cm (12.5 in.) diameter by 40.6 cm (16 in.) long cylinder with spherical end caps (test tank A). Use of these two common tank shapes provided testing for the differences between them.

The PMD consisted of 12 inner vanes that were mounted to a central standpipe as well as 12 outer vanes that follow the profile of the tank wall. Figure 1 shows the vane geometry. The tapered edge of the vanes are composed of lines and arcs fared together to produce a continuous curve. Figure 2 shows the complete vane assembly. Vanes are places one every 15 deg alternating between inner and outer vanes. Although many computational methods have been developed (see [9,13]) since the VTRE vane design was developed the majority of the VTRE design was done by layout sketches and geometric similarity to successful drop tower designs. The two sets of vanes were developed for two separate reasons. The inner vanes are designed (design "rules of thumb" and equations can be found in [11]) to locate the liquid over the inlet/outlet region and are shaped at the top to provide an unconstrained space for the maximum fill ullage bubble (corresponding to a volume of 2.5% of the tank) to rest in. The dip at the top of the vane centers the ullage bubble. It was estimated by a comparison to drop tower experiments that 24 vanes would be required to hold the liquid in place against the 10^{-4} g environment produced by shuttle attitude control thruster firing. However, the drop tower tests of [4] suggested that using more than 12 inner vanes would trap excessive amounts of liquid within the central standpipe-vane structure. As a solution outer vanes were added to the design. The outer vanes (design similar to [5]) increase the ability of the PMD to move liquid out of the standpipe-vane structure and hold it close to the inlet. There are effectively 24 vanes in that region of the tank. The outer vanes also recover any liquid which escapes out of (spilling) the inner vanes back to the bulk liquid region in a timely manner. Some common causes of spilling are thruster firings or excessive inflow rate. There may be only one or two such outer vanes in an operational system, but the VTRE was designed to recover quickly after each test to conserve shuttle mission time. An inlet baffle of fine holes was used to spread the liquid evenly between the vanes.

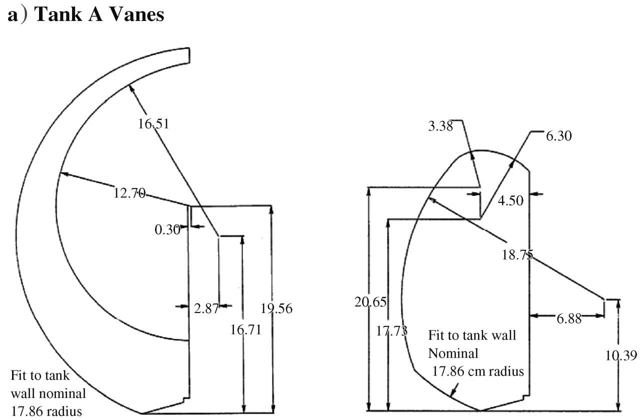
A key parameter in a vented transfer is the inflow rate at which liquid would not be captured by the vane device and would start to vent. To scale to other applications this inflow rate is converted to a nondimensional Weber number (the ratio of inertial to capillary forces). To allow comparison to [8] the length scale was arbitrarily chosen as the tank diameter divided by the number of vanes. The Weber number relationship is defined as

$$\mathrm{We} = \frac{\rho V^2 D}{\sigma N}$$

where ρ is the liquid density (grams/cm^3), σ is the liquid surface tension (N/cm), V is the average entering flow velocity (cm/s), D is the tank diameter (cm), and N is the number of outer vanes. For VTRE a series of drop tower tests were conducted using a 10.16 cm (4 in.) scale model of the VTRE tanks, and the maximum stable Weber number for inflow was found to be at a Weber number between 4 and 5.



a) Tank A Vanes



b) Tank B Vanes

Fig. 1 VTRE vane geometry (all dimensions in cm, all vanes inner edge offset 1.59 cm from tank centerline).

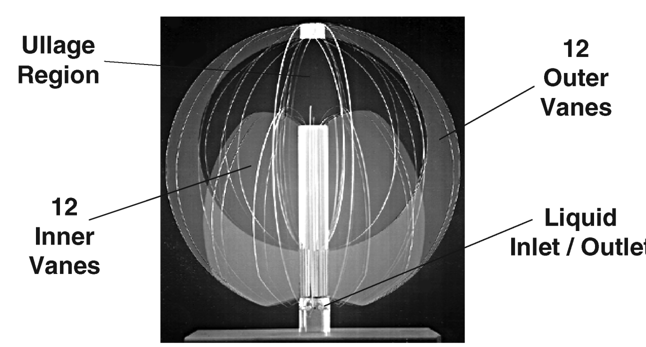


Fig. 2 VTRE vanes assembled into PMD (tank B shown, tank A similar).

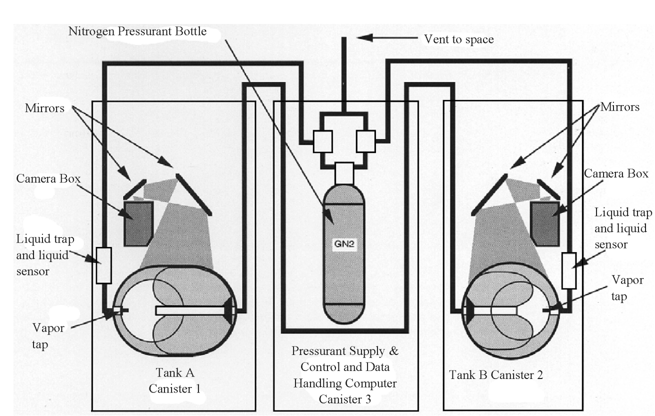


Fig. 3 VTRE experiment layout.

Table 1 Test matrix

Mission time	Test sequence	Type	Flow rate, l/min	Success	Comments
0:21:11:26	105	Transfer AB	4.85	Y	——
0:21:39:57	101	Transfer BA	4.81	Y	——
0:22:06:58	106	Transfer AB	7.38	Y	——
0:22:32:17	102	Transfer BA	7.31	Y	Gas in inflow
0:22:57:28	107	Transfer AB	9.08	Y	Gas in inflow
0:23:22:13	103	Transfer BA	9.20	Y	Gas in inflow
1:00:22:04	201	Vent A	1.43	N	——
1:00:32:58	202	Vent A	0.57	Y	——
1:00:49:30	203	Vent A	0.90	Y	——
1:01:18:47	204	Vent A	1.13	Y	——
1:01:47:35	108	Transfer AB	10.33	Y	Gas in inflow
1:21:30:46	205	Vent B	1.43	Y	——
1:21:42:28	206	Vent B	3.58	Y	——
1:22:18:35	207	Vent B	5.67	N	——
1:22:36:24	208	Vent B	4.51	Y	——
1:22:54:54	104	Transfer BA	9.84	Y	Gas in inflow
1:23:24:26	112	Transfer AB	10.33	N	20% full
1:23:32:45	213	Vent A	1.43	Y	20% full
1:23:47:38	109	Transfer BA	9.84	Y	20% full
1:23:55:05	216	Vent B	5.67	Y	20% full
2:20:00:47	110	Transfer AB	10.33	N	20% full, gas in inflow
2:20:02:19	214	Vent A	2.26	Y	20% full
2:20:12:03	113	Transfer BA	9.84	Y	20% full
2:20:18:44	217	Vent B	2.85	Y	20% full
2:20:25:50	115	Transfer AB	10.33	Y	20% full
2:20:26:56	215	Vent A	3.58	Y	20% full
2:20:34:35	114	Transfer BA	9.84	Y	20% full
2:20:42:13	218	Vent B	5.67	——	20% full
3:11:33:49	150	Upset	No flow	Y	$>7e\text{-}4$ g
3:16:57:47	151	Upset	No flow	N	g level not achieved
3:20:20:47	209	Boiling vent A	4.51	N	——

The system design of the VTRE flight experiment is shown schematically in Fig. 3. The liquid transfers were driven by a pressure difference from tank to tank. Pressurization was provided by a gaseous nitrogen (GN2) system consisting of a 4.92 liter (300 in.^{3}), 20.68 MPa (3000 psia) GN2 tank and dual regulators to reduce the pressurization system outlet pressure to 68.9 kPa gauge (10 psig). The experiment was designed to fit in three modified Hitchhiker 142 liter (5 ft^3) canisters. The center canister held the pressurization system and the experiment control electronics. The outer canisters held the test tanks and the video system. The lids were modified to provide for the required fluid and electrical connections between cans. During a transfer, one tank pressure would be raised by the pressurization system regulator and the other one vented to a lower pressure via a back pressure regulator in the vent plumbing. This use of regulators allowed similar pressure differences between the test tanks over a wide range of transfer flow rates. The flow rate was controlled by a stepper motor driven flow control valve in the center canister. This motor was programmed to provide 15 flow rates between 2.27 and 10.33 l/min. This flow rate range resulted in a tank Weber number range of 0.5–9.4. These discrete flow rates were chosen to produce Weber numbers with an 11% increase between each value. A bisectioning search algorithm was used to pick flow rates based on the results of the previous test. After four tests the stable flow rate would be bounded between two points of the 15 point range. To gain additional data the tests were repeated, but instead of starting with an empty tank and filling to more than 90% full, these tests were started with the tank 20% full and ended when the tank reached 80% full. The first test was at the highest stable flow rate of the previous tests. Then the bisectioning search algorithm was used to pick two more flow rates (three tests total).

The presence of liquid in the vent line was indicated by capacitance-type meters consisting of an acrylic tube with two copper plates bonded to the exterior. These meters measured the change in dielectric constant between the vapor and the liquid phase and produced a voltage which could be correlated to the percent of liquid by volume. A sensor was placed in each tank vent line. A sensor was also placed in the liquid inlet tubing for each tank to indicate when a tank had completely drained of liquid. Each meter was individually calibrated for all gas and all liquid voltages and the voltage assumed to vary linearly with percent liquid in-between. VTRE ground testing of this approach showed an accuracy of $\pm 10\%$ liquid volume. The core set of instrumentation for the transfer testing was these quality meters along with a turbine flow meter and the video record of the liquid transfers.

The direct tank vent tests were started by pressurizing one test tank and then maintaining the pressure for up to one hour in an attempt to force nitrogen gas into solution in the liquid. The nondimensional parameter used to determine the flow rates was the percent of the ullage volume per second of flow (at the minimum ullage volume of 5% of the tank volume). There were no data available to use to determine test parameters, so a nominal value of 1.0% per second was used. The tests were started at the fill level achieved by the previous transfer (nominally between 90 and 95% liquid). The methodology used to select a flow rate for the liquid tests was repeated for the vent testing. Fifteen different discrete flow rates were available for test, with the flow rates being chosen so that a range of vent rates of 0.4–10% per second could be achieved in testing. Again three additional tests were run to study the effect of the starting fill level. These tests were conducted at a 20% fill level.

The vent flow rate was measured by an ultrasonic flow meter that gauged the flow rate by measuring the difference in arrival time between an ultrasonic pulse traveling against the flow and a pulse traveling with the flow. One side benefit of this sensor is that the speed of sound of the vent gas mixture could also be measured. The speed of sound measurement allowed the mixture fraction of Refrigerant-113 vapor and GN2 in the vent gas to be determined. This sensor along with tank pressures and the video record of the vent testing provided the main set of test instrumentation for the vent tests.

In addition to the venting tests described above, a series of boiling tests were conducted in one tank. The same procedure as described above applied. However, the tank was vented to a sufficiently low pressure so that bubbles in the liquid were generated by boiling.

Finally, one other series of tests were conducted where the shuttle thrusters were used to impose accelerations on the liquid. The video system recorded the resulting fluid motions and the rewicking of the liquid into the steady-state low-g fluid interface shape. These tests were conducted in tank B only at a fill level of 20%. Tank B was selected for these tests due to mission timeline constraints, but it is felt because the vane geometry is similar in both tanks the results for test tank A would not be too different.

IV. Flight-Test Results

The VTRE was launched on STS-77 on 19 May 1996 as part of a cross bay Hitchhiker bridge payload called the Technology Experiments for Advancing Missions in Space. The test matrix is shown in Table 1. Most experiments were run during the crew sleep period to minimize any external disturbances during the testing. The only exceptions were the two sequences which required STS thruster firings. Success for all transfers and vents was defined by the output of the test tank vent quality meter. Exceeding a reading of 50% liquid volume for 2 s or 80% liquid volume for 1 s would indicate failure and result in termination of the test.

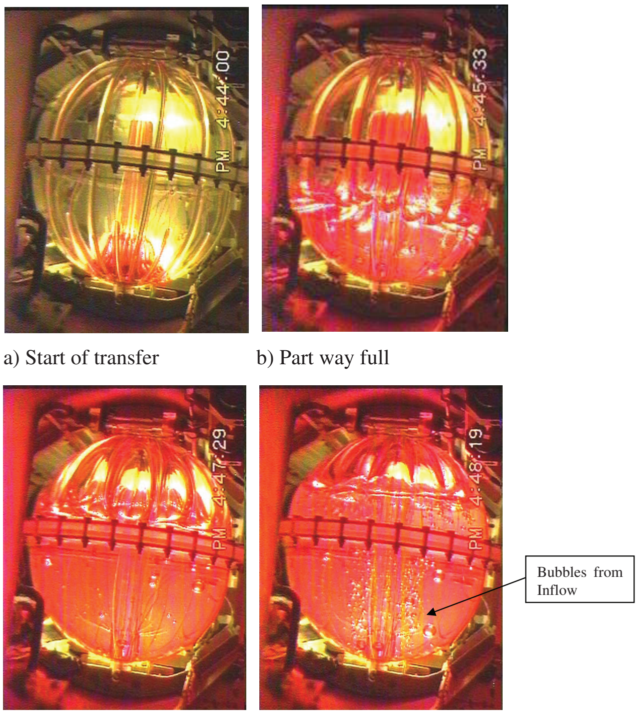
A. Transfer Tests

The data showed that the eight empty to full transfers were successful and that the critical Weber number is much higher than the preflight prediction. Video stills from a typical transfer are shown in Fig. 4. In Fig. 4a the transfer is just starting but already a column of liquid is evident around the central vane support. This area fills first. In Fig. 4b the liquid is beginning to fill along the outer vanes as well. In Fig. 4c the inner and outer vanes are at about the same level of fill. This corresponds to roughly 60–70% full. Figure 4d is at the very end of the test (90% full). Note the bubbles flowing into the tank at this point. These are caused by a suction dip that occurred in the supply tank resulting in an ingestion of gas into the inlet of the receiving tank. The outflow characteristics of the vane devices were known to be somewhat suspect at the high flow rates, but based on the drop tower testing the receiver tank was thought to be less stable and therefore to provide the limit to the transfer rates. The video showed that, as expected, the region of greatest capillary forces is at the liquid inlet/outlet and at the root of the vanes along the standpipe.

The pressure traces for the two tanks are shown in Fig. 5. As can be seen the supply tank (tank B) holds pressure fairly well with flow. The small drop off in supply tank pressure is due to the operation of the system close to the regulator overpressure maximum set point of 193 kPa (28 psia) at which point the software closed the pressurant valve for a period of time (the HH canister was pressurized to 124 kPa (18 psia) rather than the expected 103 kPA (15 psia), causing the regulators which are referenced to canister pressure to shift 19 kPa as well). The receiver tank pressure increase seen in Fig. 5 at the start of the transfer is linked to an increase in vent flow (vent flow rates are discussed later). This is due to the backpressure regulator whose pressure loss increases slightly with the increased flow rate.

The flow meter data for test 101, a typical transfer, is provided in Fig. 6. The figure shows the output of the liquid turbine flow meter and the output of the ultrasonic flow meter in the gas system (converted so that the two readings are in the same units). As can be seen in this plot, after an initial transient both flow rates move toward an on average constant flow rate. However, both of these flow rates fluctuate with the supply tank pressure transients seen in Fig. 5. Also included in this plot is the measured speed of sound of the vent gas mixture. The speed of sound is correlated to a mole fraction of GN2 variation. The speed of sound is higher at the start because GN2 relatively free of Refrigerant-113 enters the vent flow meter and then drops as the liquid vaporizes to maintain vapor pressure of Refrigerant-113 in the ullage.

The drop tower tests showed that the point of least stability in the inflow process would be at the initiation of the inflow where there is the least amount of liquid in the tank to diffuse the inflow velocity of the liquid. This was found to occur for the tests started at an initial fill level of 20%, but not for the tests started with the tank empty. It is



a) Start of transfer b) Part way full

c) Nearing end of fill d) End of fill

Fig. 4 Typical fill (test sequence 101).

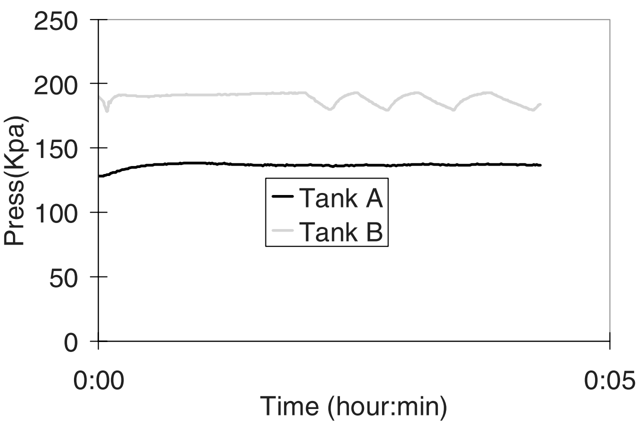


Fig. 5 System pressures during a typical transfer (test 101).

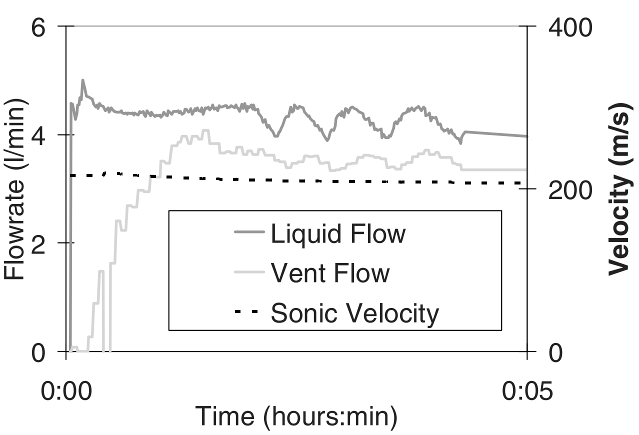


Fig. 6 Flow meter comparisons during a typical transfer (test 101).

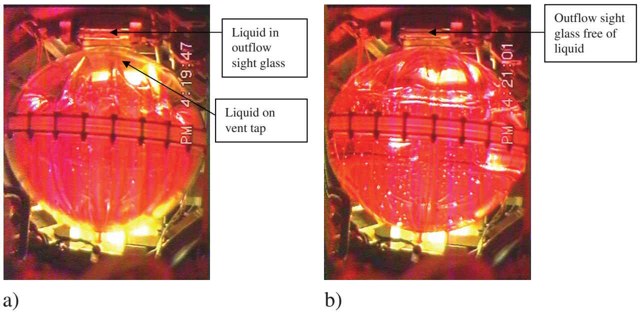


Fig. 7 a) Test 105 liquid wicks over vent. b) Test 105 end of test.

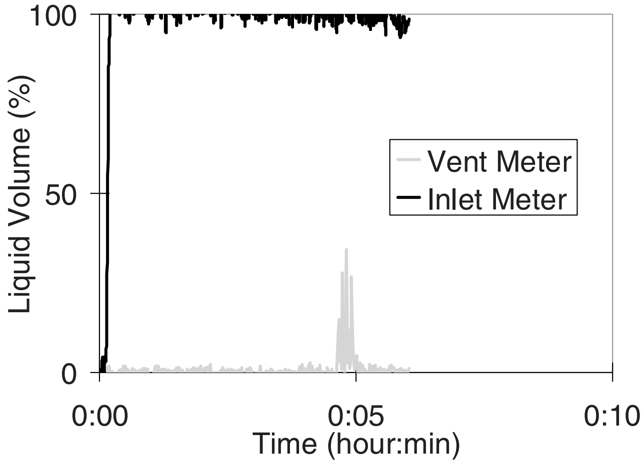


Fig. 8 Quality meter response during test 105.

believed that when the tank is initially empty, the inflow velocity is dissipated by wetting and filling the columnar region around the central vane support. When filling an initially empty tank a somewhat unstable geometry occurred when the tank was around 60–70% full. At this fill level the surface curvatures created by inner and outer vanes tended to cancel each other out. This flattened a broad region of interface, lowering the force generated by the free surface which is a function of surface curvature. This made it easy for the inflow liquid to transfer from the inner vanes to the vent region. Video of tests 105, 107, and 108 show two-phase flow out the vent at this fill level (but not great enough liquid fraction to fail our success criteria). Figure 7a shows test 105 at this stage. Liquid has escaped from the inner vanes and wet the vent. After several seconds of inflow the interface shape again made the situation less likely to occur. Figure 7b shows test 105 at the end. Liquid no longer wets the vent. Quality meter data for test 105 are shown in Fig. 8. Here the inlet and vent quality meter outputs are shown. As can be seen in the plot, the inlet meter, after an initial transient, provides an indication of 100% liquid during the entire transfer, whereas the vent sensor varies with the amount of liquid in the vent. This figure shows a brief spike of two-phase flow, but does not exceed the 50% liquid volume threshold.

Further transfer tests were conducted to determine the difference in the inflow to a partially full tank (∼20% fill level) vs the initially empty tank primary tests. Based on their observation of the drop tower testing the authors speculated that the critical inflow rate should be greater for a partially full tank because there would be liquid over the tank inlet to diffuse the flow at the initiation of the transfer (the inflow rate at the start of the transfer is the greatest because the static pressure difference between the tanks is also the greatest). The in-flight data showed the reverse to be true. In many of the partially full tank tests, the initial inflow surge would simply ride up the standpipe and would push the liquid out of the center vanes into the region of the vent tube, resulting in venting of the liquid as shown in Fig. 9. Tests 110, 112, and 115 fail because of this. Tests 109 and 113 vent two-phase flow at this point but continue on.

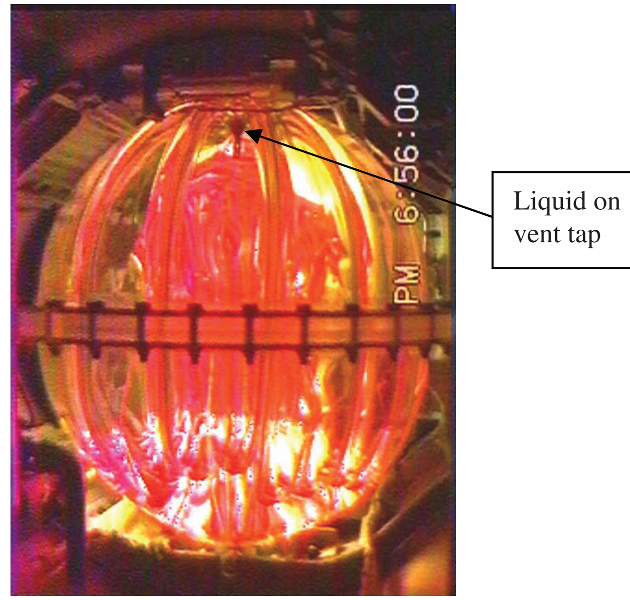


Fig. 9 Liquid inflow escapes from top (test 109).

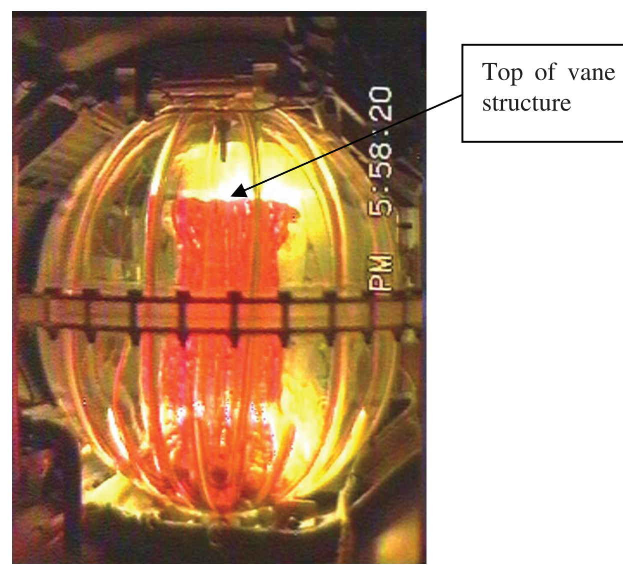


Fig. 10 Vanes turn back liquid inflow (test 104).

Figure 10 shows a similar time during test 104 (a test starting from empty). Here the inflow surge is captured by the vanes and the inflow could continue as planned.

The response of the quality meters to the venting of liquid during the partially full transfer is shown in Fig. 11. The vent meter shows all gas then subsequently venting of liquid shortly after the transfer begins returning to all gas at the end. The liquid volume fraction was not great enough to terminate the transfer but liquid venting can be seen in the video data.

B. Vent Tests

Six of the eight primary (90% full) vent tests conducted were successful. Figure 12 shows the test tank at the end of a typical successful vent test. For test tank A the critical point was found to be a vent rate corresponding to ∼0.075% of tank volume per second (∼.708 1/ min) whereas for tank B a stable flow rate of 4 times this value was found in the testing. The primary reason for this disparity is the differences in tank ullage volumes between the tank A and the tank B vents. The vent tests for tank A had an ullage volume of ∼6–7% whereas the ullage volume in the tank B testing was closer to 10% (This is confirmed by a slower pressure reduction for the tank B

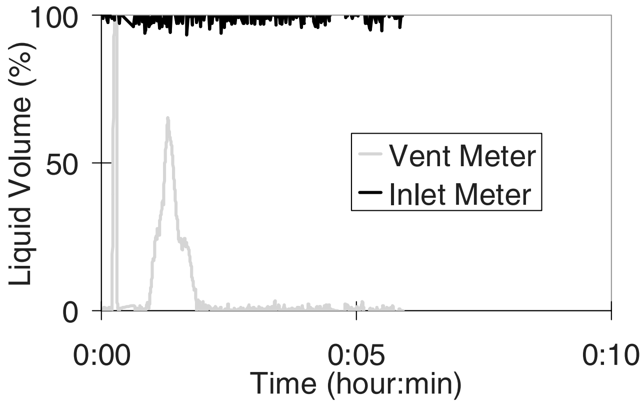


Fig. 11 Quality meter response to liquid venting during test 109.

than tank A, in tests with the same vent flow rate). The vent tests did show that a nonsettled tank can be vented without risk of liquid venting using a vane-type PMD. The video record of the venting showed very little bubble formation until the tank pressure dropped to the pressure corresponding to the saturation level of the dissolved pressurant, at which point nitrogen bubbles would begin to appear and grow. The key to being able to sustain a vent using a vane-type PMD is that these bubbles must grow to a size large enough for the vane device to effectively pump the bubbles to the ullage region (as opposed to what occurs in a one-g environment where numerous small bubbles form and are then transported to the gas region via buoyancy). In low-g a bubble will not be pumped in any direction unless a pressure gradient is established across the surface. Once the bubble contacts two or more vanes, the bubble is deformed from the low energy spherical shape to a tapered shape with a preference to move in the direction where the taper is wider. The VTRE PMD is designed to pump a minimum size bubble of 1.27 cm (0.5 in.) in diameter (this will only occur in the region of the tank inlet/outlet) up to a maximum size of 10.67 cm (4.2 in.) diameter in the vent region (corresponding to a volume of 2.5% of the tank).

The video record showed that the bubbles did indeed grow to a size large enough to be pumped by the PMD. This process occurred via vapor generation inside the bubbles causing them to grow in size, and via two bubbles coalescencing into one larger bubble. The bubble coalescence method appeared to be the dominant one. Any time two bubbles would contact for more than an instant, the two would grow into one bubble (which is supported by a free surface energy analysis showing one large bubble being a lower energy state than two smaller ones). The time for the combination roughly correlated with the time for the very thin remaining liquid film between the two bubbles to vaporize, which would occur within 1 s or so. This observation also applied when the individual bubbles contacted the main tank ullage. Sometimes very large bubbles would contact the ullage resulting in an off centered ullage volume once the two volumes joined. The PMD would simply recenter this volume over the standpipe. This recentering occurred very quickly (within 4–5 s), which was much faster than predicted.

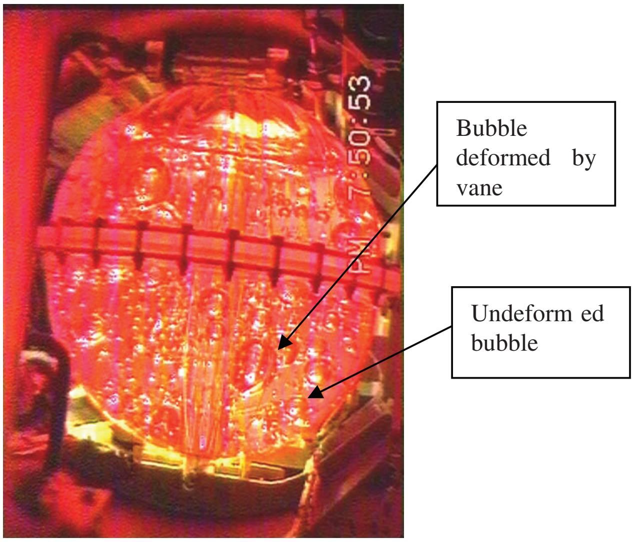


Fig. 12 Typical vent (test 204).

The pressure data during one vent are provided in Fig. 13. Here the tank pressure can be seen to drop very rapidly at the start with the pressure reduction rate gradually decreasing. The decrease in the pressure reduction rate is due to the reduction in flow rate with decreasing tank pressure (the vent flow control valve was choked during these vents) and was also due to the nitrogen bubbles coming out of the solution, resulting in an increase in gas volume that must be vented from the tank to achieve a net pressure reduction. Figure 14 provides the output of the ultrasonic flow meter during this test. The flow rate is roughly constant varying between 0.708 and 0.850 l/min, whereas the mole fraction (as calculated from the measured speed of sound) showed a decrease from 48% nitrogen initially to a value of 13% nitrogen at the end. These data match the pretest predictions for the mole fraction (simply based on the partial pressures of the two gases). This model correlation confirms the assumption that the ullage gases are a well-mixed homogenous mixture, with the Refrigerant-113 partial pressure corresponding to the saturation pressure of the liquid.

As with the transfer testing, vent tests were conducted on tanks that were only 20% full. These tests showed no issues because the ullage volume was so large. Considerably higher vent flow rates than were possible with the VTRE system would have been required to obtain an unstable vent for these fill levels.

The last vent tests consisted of boiling vent tests. Since at ambient temperature (which was the design environment for VTRE) the saturation pressure of Refrigerant-113 is ~34.5 kPa, test tank B was first vented to this pressure to begin the testing. The boiling vent tests were not as successful as the previous nitrogen venting tests for two reasons. First, the test tanks were designed to be thermally coupled to the HH canister environment to ensure the Refrigerant-113 would not freeze. This caused the heat removal via venting to be much lower than the heat input from the environment, resulting in a net boiling of the liquid without any actual pressure reduction. Second, the bubbles generated by boiling did not tend to coalesce and the tank simply filled up with a great amount of very small bubbles. This resulted in liquid venting due to the swelling of the liquid volume.

C. Liquid Recovery Tests

Two tests looked at the response of the system to a high thrust and a low thrust disturbance. Because the thruster firings that were used to generate these accelerations were not dedicated to VTRE (i.e., VTRE piggybacked off another planned maneuver) the thrust levels were not controllable, only the duration. For the high thrust acceleration a burn time of 15 s was chosen [using two of the Orbiter primary reaction control system (RCS) jets] since that represented a factor of 4 on the predicted settling time for the liquid (thereby providing enough time to damp out most residual oscillations in the liquid). The liquid did indeed settle over the tank vent as predicted within this time and then rewicked back into the low-g orientation within 20–30 s. Figure 15 shows the liquid during the high thrust period. Liquid position before and after thrust is similar to Fig. 4b. The pretest predictions were for a time of 2–3 min, therefore the wicking action of the vanes is much greater than previously thought. Accelerometers were flown to record the acceleration levels of the firing, with the planned acceleration to be in the low 10^{-4} g range. The accelerometer output saturated at the maximum reading of 7×10^{-4} g's during the firing meaning that the thrust level was much higher than originally planned (the planning was based on use of one RCS jet only). This test showed the robustness of a vane device system. The liquid was upset out of the vane device for a total time of less than 1 min after a very high level acceleration event of a fairly long duration. The second test showed similar thrust levels but for only 1–2 s. The liquid did slosh around the tank and then quickly rewicked into the low-g orientation.

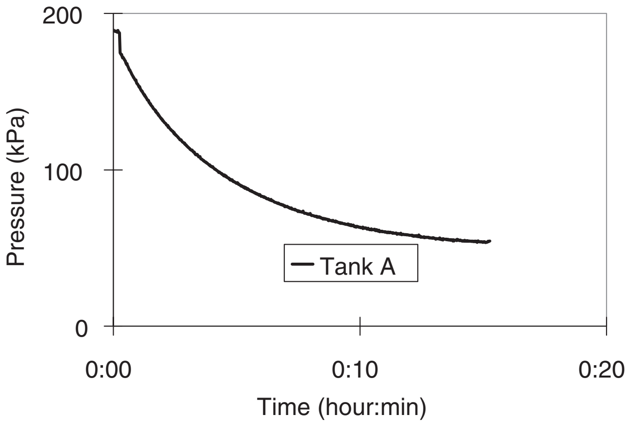


Fig. 13 Tank pressure during a tank vent.

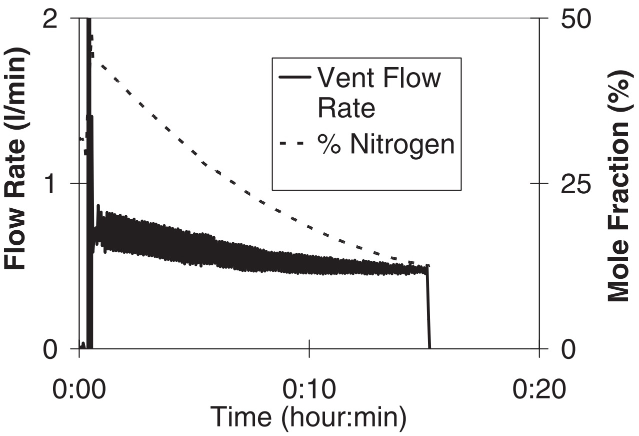


Fig. 14 Measured flow rate and mole fraction during a tank vent.

Fig. 15 Fluid position during shuttle thruster firing.

V. Conclusions

The VTRE flight experiment on STS-77 confirmed the design approaches presently used in the development of vane-type PMD's for use in resupply and tank venting situations and provided the first practical demonstration of an autonomous liquid transfer system. Transfers were more stable than drop tower testing would indicate and show that rapid fills can be achieved. Liquid was retained successfully at the highest flow rate tested (10.33 l/min). Venting tests show that liquid-free vents can be achieved. Liquid-free vents were achieved for both tanks, although at a higher flow rate (4.51 l/min) for the spherical tank than the tank with a short barrel section (1.13 l/min). The liquid recovery test showed rewicking of liquid into the PMD after thruster firing was quicker than pretest predictions. Pretest estimates based on a dimensionless time constant obtained by comparing acceleration and vane pressure forces had predicted times as long as 9.5 min. Recovery from a thruster firing which moved the liquid to the opposite end of the tank from the PMD was achieved in 30 s. The objectives of VTRE were all achieved. The VTRE was flown in 1996 but the data set remains unique and relevant. The video provided one of the few direct observations of PMD behavior for extended times in low gravity. Important observations include observation of the behavior of vane devices during the complete fill of tanks with liquid in low gravity; observation of the ability of vane devices to clear bubbles during venting in low gravity; and observation of the refill of a liquid vane device after high-g maneuvers on orbit.

Citations by recent journal papers (such as [13]) indicate the information obtained by this experiment continues to be relevant today. Recent renewed interest in on-orbit fluid transfer in support of space exploration makes this experiment relevant to current NASA goals as well. The vaned transfer methodology proven by this experiment remains one of the few flight demonstrated techniques for on-orbit fluid transfer.

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